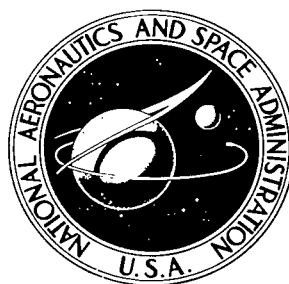


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A STUDY OF DISPLAY SYSTEMS FOR
MANUAL GUIDANCE OF LARGE LAUNCH
VEHICLES UTILIZING THE X-15 AIRPLANE
AND FLIGHT SIMULATORS

by Armando E. Lopez, Gordon H. Hardy, and Ronald M. Gerdes
Ames Research Center
Moffett Field, Calif.



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NOTATION

a_x	longitudinal acceleration
$e_{\Delta h}^2$	integrated squared error in altitude, $\int_{t_{ig}}^{t_{co}} (\Delta h)^2 dt / 10^7$
$e_{\Delta \dot{h}}^2$	integrated squared error in altitude rate, $\int_{t_{ig}}^{t_{co}} (\Delta \dot{h})^2 dt / 10^5$
h	altitude, ft
\dot{h}	altitude rate, ft/sec
h_{ap}	apogee altitude
G_{dB}	$20 \log_{10} \text{amplitude ratio} $
K	gain constant
K_h	display sensitivity of altitude error, in./ft
$K_{\dot{h}}$	display sensitivity of altitude rate error, in./ft/sec
q	dynamic pressure, lb/ft ²
s	Laplace operator
T	time constant, sec
t	time, sec
Y_p	transfer function for human pilot
Δh	altitude error, $h - h_n$, ft
$\Delta \dot{h}$	altitude rate error, $\dot{h} - \dot{h}_n$, ft/sec
$\Delta \epsilon$	$K_h \Delta h + K_{\dot{h}} \Delta \dot{h}$, combined error signal
θ	attitude angle of vehicle with respect to local horizontal, deg
σ_{ap}	standard deviation of calculated apogee altitude, ft
ϕ	phase, deg
ω	frequency, rad/sec

Subscripts

co	cut off (thrust termination)
ig	ignition
n	nominal

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SUMMARY

A study has been made of the effectiveness of display systems for manually guiding launch vehicles with the accuracy required for earth orbit injection. Three guidance systems were investigated in two flight simulators. One guidance display system was implemented on the X-15 research airplane to determine the system's effectiveness in a real flight environment.

All three guidance schemes presented to the pilot the errors in altitude and altitude rate with respect to a reference trajectory. The pilot's task was to null the error signals by controlling the vehicle so that its trajectory matched, as closely as possible, the reference trajectory.

The results of the simulator study show that the human pilot is capable of guiding a vehicle to a reference trajectory within the accuracy requirements of current manned spacecraft launch vehicles. The results of two X-15 flights with one of the guidance systems indicated no adverse effects of real flight environment.

INTRODUCTION

Presently, automatic flight control systems are used for the primary guidance and control of operational manned launch vehicles. The crew does not actively participate within either the guidance or control loop. The task of the crew during the boost phase is to monitor the automatic control system, to detect malfunctions, to manipulate switches, and to abort the flight in case of a major malfunction.

Investigations have shown that a manual backup guidance and control system can compensate for the most probable failures in the primary system and can increase the overall mission reliability. A study of the pilot controlling the first stage of the Saturn vehicle (ref. 1) indicated that the pilot could increase the probability of mission success for certain simulated automatic-system failures. Another study (ref. 2) showed that even with a crude digital-type display, the human pilot could guide the upper stages of the Saturn vehicle into a near-earth circular orbit with the required injection accuracy. In the study reported in reference 3, the pilot used various

guidance display systems to guide and control the upper stages of a large launch vehicle. In addition to these fixed-cockpit studies, centrifuge studies have demonstrated that there is no measurable decrease in pilot performance at the acceleration levels associated with current launch vehicles (refs. 1 and 4).

As part of this coordinated research effort into manual guidance for large launch vehicles, it was felt that data taken under flight conditions approximating as nearly as possible those of the Saturn boost would be of great value in assessing the effects of a real flight environment. A comparison indicated that the characteristics of the X-15 and Saturn boost phase were sufficiently similar that the X-15 research airplane could be used in determining the effects of flight environment.

The objective of this investigation was to study three manual guidance display systems during the boost phase of the X-15 airplane. Prior to these flights, a series of simulated flights were made to obtain baseline data for comparison with the flight data. It was intended that all three display systems used in the simulations would be used as primary boost guidance during actual flights with the X-15, but unfortunately, only two flights with one of the systems were completed before the termination of the X-15 program.

This report reviews the similarities between the Saturn and X-15 trajectories and control systems during boost and discusses the results of the simulation data and the limited flight results. The data are discussed in terms of trajectory control during boost, errors in altitude and altitude rate with respect to a nominal trajectory and pilot ratings of these systems.

COMPARISON OF SATURN V AND X-15

Flight Profiles

The flight parameters during boost for a high altitude flight of the X-15 are compared in figure 1 with the first stage of the Saturn V vehicle at similar altitudes and velocities. The time indicated in this figure is the time from launch of the X-15 from the mother ship. The time history for the Saturn vehicle has been shifted to give maximum correlation with the flight parameters of the X-15. The dissimilarity in the first portion of the flight is to be expected, inasmuch as the comparison is between a vertical and horizontal launch. However, the parameters that are critical for comparing the X-15 and Saturn-launch-vehicle manual guidance and control systems (aerodynamic pressure and longitudinal acceleration) agree well.

Attitude Control Systems

The adaptive flight control system on board the X-15 vehicle is a high-gain, rate-command system in pitch and roll and a high-gain damper system about the yaw axis. The gain of the system is variable so as to provide constant airplane response throughout the flight envelope. The system utilizes

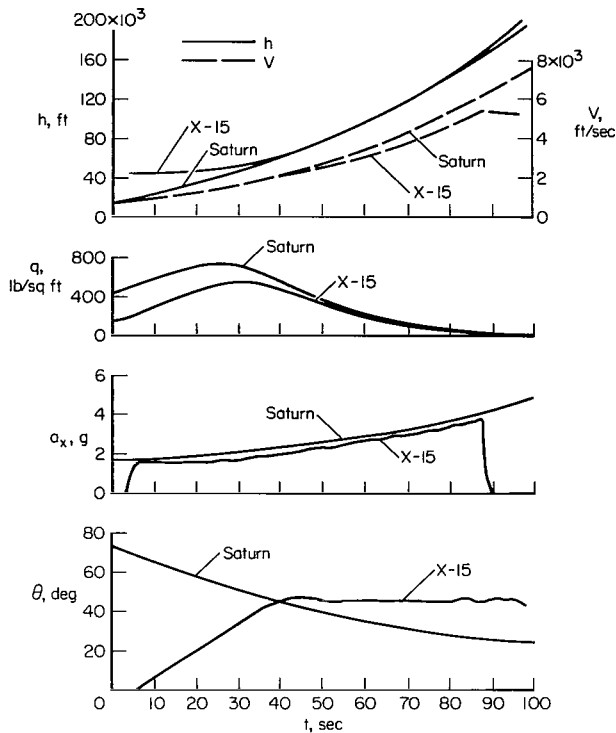


Figure 1.- Comparison of X-15 and typical Saturn C-5 boost.

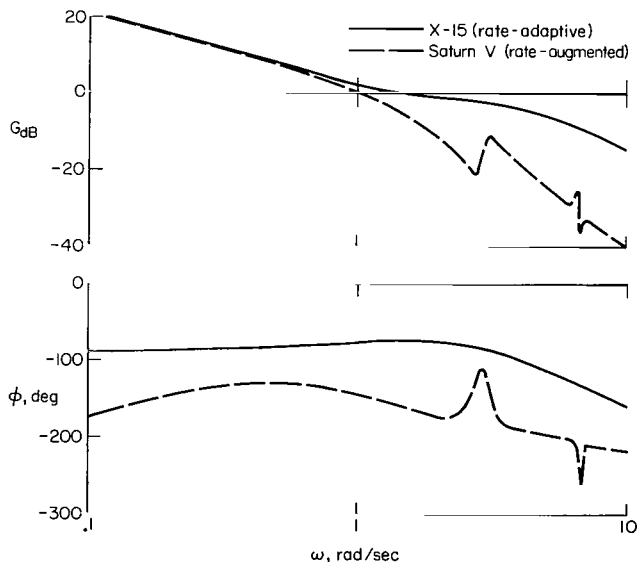


Figure 2.- Pitch attitude frequency response of X-15 and Saturn V vehicles.

both aerodynamic controls for high-dynamic-pressure conditions and reaction controls for low-dynamic-pressure conditions to provide control over the entire flight regime. This system is described in detail in reference 5.

The pitch-attitude frequency response to longitudinal stick position for the X-15 (fig. 2) indicates that within the frequency range generally associated with manual control ($\omega \leq 1$), the airplane longitudinal response approximates a rate-command system (i.e., approximately 20 dB drop per decade). The flight conditions are those approximately midway through the boost phase for a high-altitude flight ($V = 3000$ ft/sec or 1000 m/sec and $h = 85,000$ ft or 28 km). Since the control system is a high-gain adaptive system, the dynamic response characteristics do not vary significantly throughout the boost phase from what is shown in figure 2.

The attitude response of the Saturn vehicle (also presented in fig. 2) indicates that a typical manual attitude control system for this vehicle also approximates a rate-command system within the frequency range generally associated with manual control. The control system characteristics depicted are those associated with the most critical portion of the flight (i.e., the region of highest dynamic pressure, $V = 1500$ ft/sec or 485 m/sec and $h = 40,000$ ft or 13 km). These conditions and control systems are described in reference 1.

The rapid increases and decreases in phase at 3 and 7 radians per second associated with the Saturn vehicle are produced by the sloshing of fuel and the first bending mode, respectively. These two items were not considered in evaluating the frequency response of the X-15 airplane.

The significant conclusion from the data is that the pilot will respond, in the attitude control loop of both vehicles, in approximately the same manner. In other words, within a control loop where the controlled element may be described by a rate-command system (K/s), the analytical function that describes the pilot may be approximated by Ke^{-Ts} (i.e., a simple gain and a pure time delay, ref. 6). This is the simplest form for describing a pilot since it involves no lead or lag terms.

GUIDANCE DISPLAY SYSTEMS

Preliminary studies on manual guidance of the Saturn launch vehicle indicated that three display systems were appropriate for manual guidance to a near earth circular orbit (ref. 2). Further studies showed that the systems could be implemented on the X-15 airplane without major modifications to the existing on-board computer and instrumentation system. These systems are

referred to as A, B, and C in the schematic diagram in figure 3.

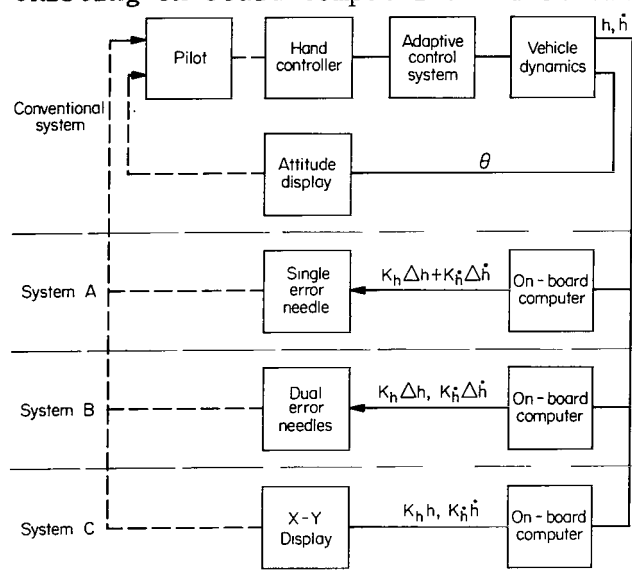


Figure 3.- Schematic block diagram of guidance systems for X-15.

The displays associated with these systems are depicted in figure 4. Each system displayed the trajectory errors (Δh and $\Delta \dot{h}$) with respect to a nominal trajectory in a slightly different manner (see figure 4); each required different on-board computation and each involved a different mode of pilot interpretation.

In system A, the instantaneous values of altitude and altitude rate are subtracted from the reference values which are stored within the on-board computer. The resultant signals are multiplied by appropriate scale factors and the sum of these two signals is presented as a deflection of the horizontal-flight-director needle on the attitude indicator. The pilot is only required to respond to a single error display signal, $\Delta \epsilon$.

In system B, the individual signals of altitude error and altitude-rate error are presented separately (Δh on the horizontal-flight-director needle and $\Delta \dot{h}$ on another needle). With this system

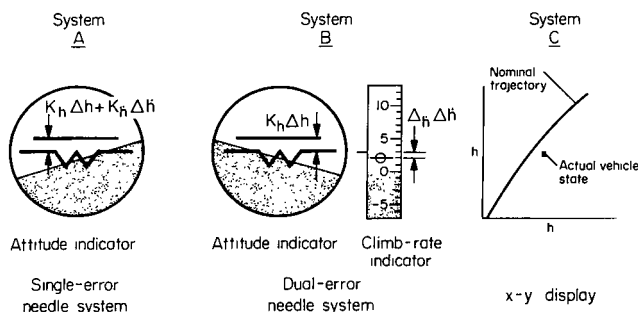


Figure 4.- Guidance display systems.

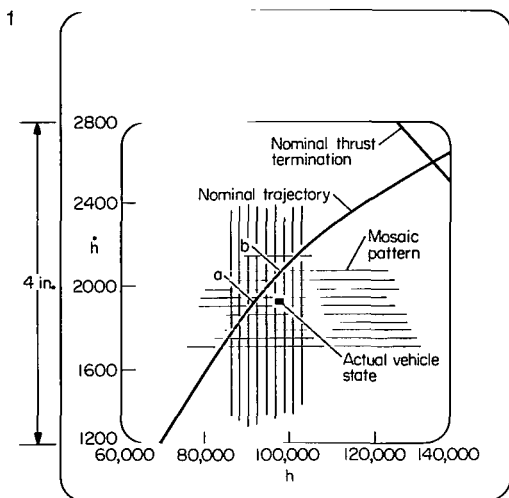


Figure 5.- Schematic view of x-y display.

there might be less on-board computation but there would be an additional display that would necessitate additional interpretation by the pilot.

In system C, the altitude and altitude rate are displayed on an x-y type display upon which the reference trajectory has been etched. The x-y display used in this study was a modification of the X-15 energy management display system described in reference 7. It utilizes a gas discharge tube mounted below the attitude indicator, which resembles a cathode ray tube except that discrete lights are spaced in a 10 by 10 mosaic for each square inch of the 4- by 4-inch display (see fig. 5). The parameters displayed were computed and updated three times per second. This system requires very

little computation. Since the nominal trajectory is etched on the faceplate, all comparisons with the nominal trajectory are performed by the pilot.

The displays used in systems A and B are "fly-to" systems; that is, an upward deflection of the needle is an indication to the pilot that the vehicle is below the nominal trajectory and that he should rotate the vehicle to a higher climb rate. The display used in system C is an error display system, that is, when the "bug" is below the etched trajectory, the vehicle is below the nominal trajectory.

SIMULATION

Three guidance systems were used in both fixed-cockpit simulator studies. A series of simulated flights was conducted using a simplified X-15 simulation at Ames. These tests were aimed at determining basic display configurations and sensitivities. The rest of the simulation data were obtained from the high-fidelity X-15 simulator at Flight Research Center (FRC). The purpose of those tests was to refine the display and obtain additional baseline data. The FRC simulation is relatively complete, duplicating to a large extent actual flight hardware including actual hydraulic and control-system hardware.

Three research pilots who have had wide experience with many types of aircraft and control systems participated in the X-15 simulator study at Ames, and two of these pilots and two X-15 research pilots participated in the study at FRC. There were no significant differences between the guidance system performance measured on the X-15 and Ames fixed-cockpit simulators, nor were there any noticeable differences in performance measurements between the Ames and FRC pilots on the X-15 flight simulator. However, the X-15 research pilots rated the guidance systems slightly better than the Ames pilots did, probably because of their familiarity with the control system and the conventional guidance system (θ profile) of the X-15.

RESULTS AND DISCUSSION

Effects of Display Sensitivity

The effects of display sensitivity and configuration on the pilots ability to guide to an acceptable trajectory using the three guidance display systems were evaluated as illustrated in figures 6 and 7. These data were used to select the sensitivity for the flight experiments. Three measurements of performance were made: (a) integrated squared error; (b) standard deviation of apogee-altitude error; and (c) pilot's rating (ref. 8).

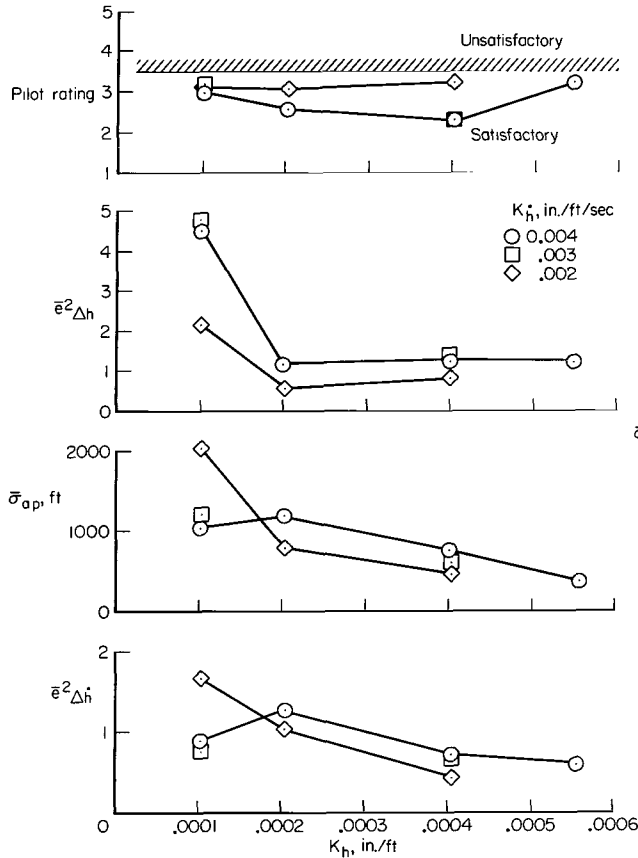


Figure 6.- Effects of display sensitivity, single-error-needle system.

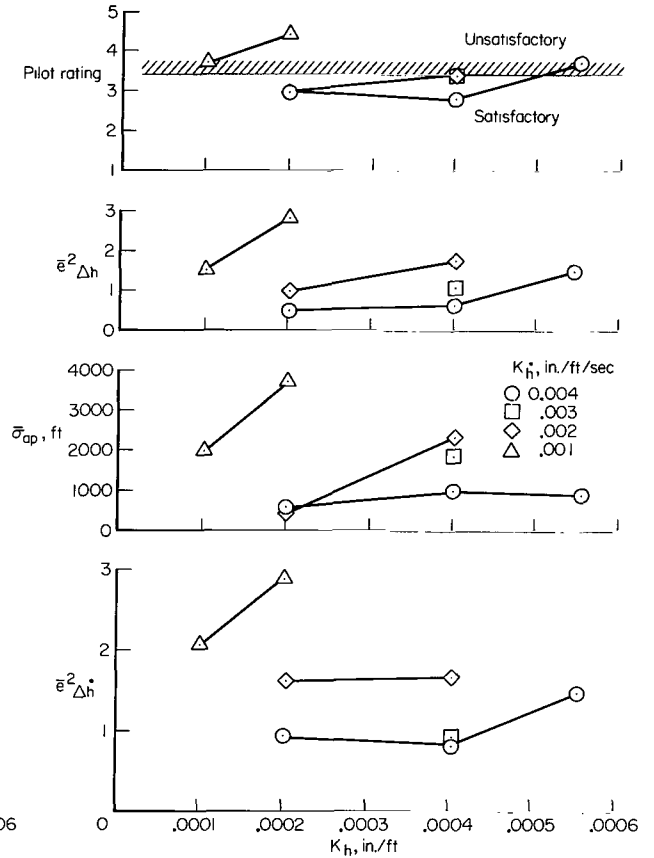


Figure 7.- Effects of display sensitivity, dual-error-needle system.

The integrated squared error was used as a measure of how close the pilot flew the vehicle to the desired trajectory throughout the simulated flight. The error in apogee altitude was calculated from the guidance errors at thrust termination. The formula used was based on the apogee altitude being equal to the summation of the vertical components of the potential and kinetic energy (considering constant gravity and a flat earth),

$$h_{ap} = h_{co} + \frac{1}{2} \frac{\dot{h}_{co}^2}{g}$$

so that the approximate expression for apogee altitude error is

$$\Delta h_{ap} = \Delta h_{co} + \frac{\dot{h}_{co} n}{g} \Delta \dot{h}_{co}$$

The standard deviation (σ) of the calculated apogee-altitude error for each pilot was used as an indication of the accuracy with which the pilot could match the vertical energy conditions of the reference trajectory at thrust termination. The data plotted represent the average σ for all the pilots. The pilot's rating was used as a subjective indication of the relative difficulty of the task involved.

The range over which the sensitivities were varied was dictated by launch vehicle guidance accuracy requirements and by the limitations of the computer system. The error needle systems (A and B) were studied with values of K_h , the sensitivity of the altitude-rate-error signal, from 0.001 to 0.004 (1 in. deflection equivalent to 1000 and 250 ft/sec altitude-rate error, respectively) and with values of K_h , the sensitivity of the altitude-error signal, from 0.0001 to 0.00055 (1 in. deflection equivalent to 10,000 and 1800 ft altitude error, respectively).

The sensitivity of the x-y type display was dictated by the physical size of the display (fig. 5) and the range of altitudes and altitude rates that occurred during the boost phase of flight. At the completion of the initial pull-up maneuver, the climb rate was approximately 1200 ft/sec at approximately 60,000 ft of altitude. At thrust termination the climb rate was approximately 2600 ft/sec at an altitude of about 140,000 ft. These values set the maximum and minimum values on the x-y display.

The data presented (figs. 6 and 7) are the results for various sensitivities of the error-needle display systems. Each data point represents the average of many test runs (up to 16, from the simulations at FRC and Ames) at given values of the two sensitivities.

Single-error-needle system.- As K_h , the sensitivity of the altitude-error signal, was increased, performance with the single-error-needle system generally improved (fig. 6). The average integrated altitude error $\bar{e}_{\Delta h}^2$ showed a marked decrease as K_h was increased from 0.0001 to 0.0002. However, no additional improvement occurred when K_h was increased beyond 0.0002. The average standard deviation of apogee-altitude error, $\bar{\sigma}_{ap}$, and the average integrated altitude-rate error, $\bar{e}_{\Delta \dot{h}}^2$, generally showed improved performance as K_h was increased.

The effects of changes in K_h , the sensitivity of the altitude-rate-error signal, is shown in figure 6. Although the pilots indicated a preference for the more sensitive altitude-rate-error display ($K_h = 0.004$), in the range of preferred sensitivity of the altitude-error display ($K_h \geq 0.0002$) the objective performance measurements indicated a slight improvement with the less sensitive display ($K_h = 0.002$).

Dual-error-needle system.- The effects on the performance measurements of changes in the display sensitivity of the dual-error-needle system are

shown in figure 7. These data show a distinct improvement in all performance measurements with the more sensitive altitude-rate-error signal ($K_h = 0.004$). With K_h set at 0.004, the best performance was obtained with K_h set between 0.0002 and 0.0004.

On the basis of these data, the display sensitivity for the flight experiments was set at $K_h = 0.0002$ and $K_h = 0.004$. According to figures 6 and 7, at these sensitivities the pilot should be able to attain the desired apogee altitude within approximately 1500 feet using either display system A or B.

x-y Display.- The integrated errors in altitude and altitude rate are not presented for the x-y display since they do not reflect the ability of the pilot to match the trajectory presented to him as a plot of \dot{h} vs. h . To illustrate this point, we can refer to figure 5. For example, if the reference trajectory called for the altitude and altitude rate corresponding to position a but a combination of errors placed the "bug" at position b, the pilot could not distinguish any error. This would result in excessively large integrated errors. However, as long as the pilot terminated his thrust at the indicated proper position, the sum of the vertical components of kinetic and potential energy would place the vehicle at the proper apogee altitude.

Using the x-y display, the pilot was able to control the vehicle so that the calculated apogee altitude error had a standard deviation of slightly over 2000 ft. The trajectory control throughout the flight was not as precise as with either of the two error-needle systems.

The following data are presented for comparing the x-y display to the error-needle systems. The sensitivity of the error-needle system is that selected for the flight experiments.

	Single needle	Dual needle	x-y Display
K_h	0.0002	0.0002	0.0005
K_h	0.004	0.004	0.0025
Pilot's rating (average)	2.7	3.0	2.5
$\bar{\sigma}_{ap}$, ft	1200	600	2100

Although the pilots rated the x-y display somewhat better than the other systems, the standard deviation in apogee altitude was larger. This error may be attributable, at least in part, to two features of the x-y display; the grossness of the sensitivity compared to that of the error-needle system and the discreteness of the display (see fig. 5).

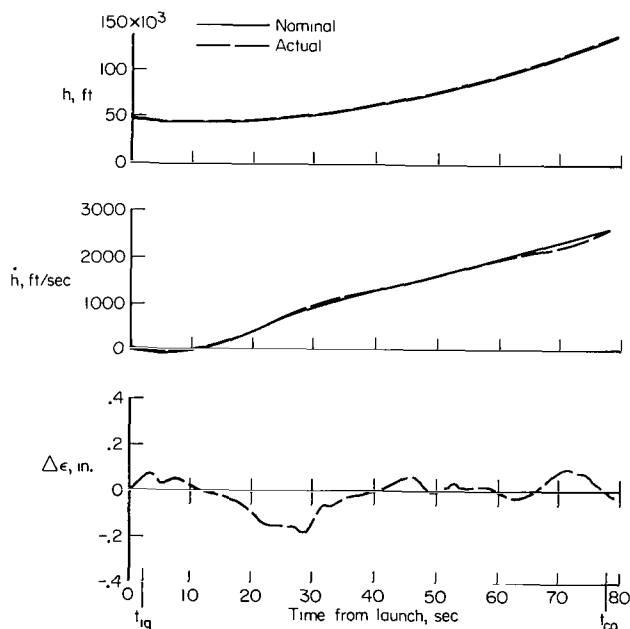
One significant comment made by one of the X-15 research pilots was "actual physical display is poor (i.e., because it has parallax and a non-continuous tracking bug), but concept is great. If properly mechanized with

cross-pointers or an accurate electron tube, this could be a real winner, particularly if the pilot had all the flight parameters displayed (as I did) for a 'how-goes-it' cross checking."

Pilot Techniques

The pilot's task during this study was to guide the X-15, using the display provided, so that the trajectory would match, as closely as possible, the reference trajectory. Following the initial pull-up maneuver, the pilot attempted to match the altitude and altitude-rate profile of the reference trajectory until thrust termination. Although this study was devoted predominantly to guidance and control in the vertical plane, the pilot was still subjected to the workload normally associated with guidance and control about the other axes as well as monitoring all flight systems and other experiments on board the X-15 airplane.

Single-error-needle system.- The pilots' response to the errors in guidance differed slightly with each display system. With the single-error-needle system, generally the pilots' response resembled the tracking of an error signal in a single-axis compensatory task. They attempted to null the error signal as rapidly as possible, resulting in an oscillation of the error signal, $\Delta\epsilon$, about the null throughout the boost phase (see fig. 8(a)).

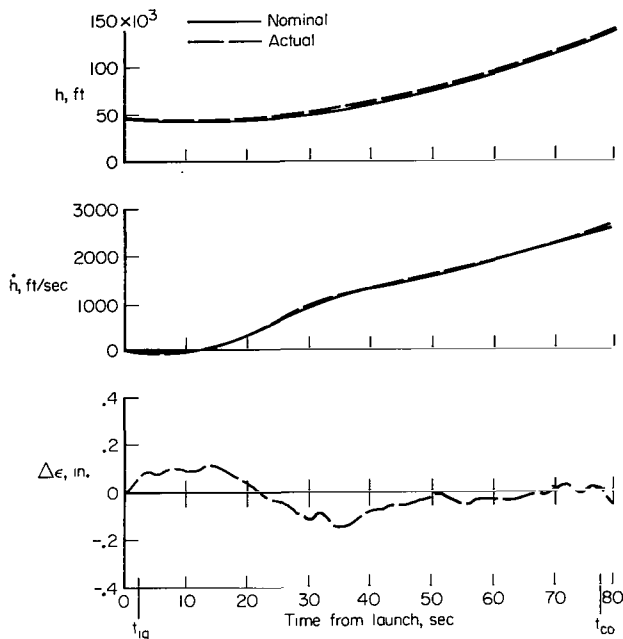


(a) Single-error-needle system.

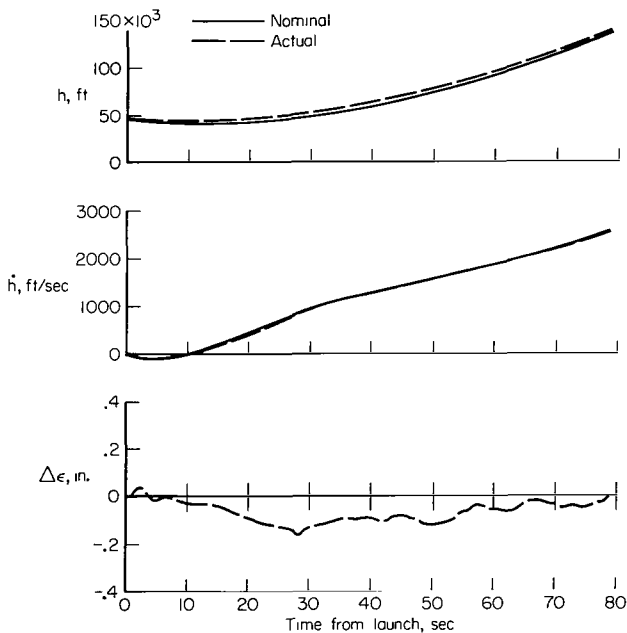
Figure 8.- Time history of simulated flight, FRC simulator.

During the series of simulator runs with the single-error-needle system, the oscillations about the null point of the display were very lightly damped and appeared to have a period of oscillation between 12 and 20 seconds. A simple analysis to determine what system characteristics with a pilot in the loop would cause this sort of behavior indicated that if the transfer function describing the pilot were a simple gain and transport delay, even modest gains would result in a lightly damped oscillation of about 18 seconds. This analysis is described in the appendix.

Dual-error-needle system.- While using the dual-error-needle system, the pilot appeared to concentrate more on the end-point conditions. After a few practice runs he could determine how much error in altitude rate was sufficient to overcome an altitude error in the opposite direction and arrive at the desired end-point conditions at thrust termination. Generally,



(b) Dual-error-needle system.



(c) x-y display.

Figure 8.- Concluded.

the error signal would approach the null asymptotically, as illustrated in the typical time history in figure 8(b).

x-y Display system.- The pilot responded to the error in the x-y display in approximately the same manner as he did with the dual-error-needle system; that is, from the position and direction of movement of the display "bug" he would determine the corrective action necessary to arrive at the end-point conditions. His response generally resulted in an asymptotic approach of the error signal to the null position at thrust termination. This is illustrated by a typical time history in figure 8(c).

One obvious advantage of the x-y display is the ease in handling off-design conditions. With systems A and B large errors would saturate the display. The x-y display, because of its relative insensitivity, could portray large errors without exceeding its range. The off-design conditions investigated were errors in thrust level (± 500 lb), ignition time (± 5 sec), and initial altitude (± 1000 ft). Within these limitations, the pilot was able to reach the end-point conditions (using the x-y display) within the required accuracy. In general, it was felt that as long as the cut-off conditions were within the thrust capability of the vehicle, the desired end-point conditions could be obtained with the x-y display.

Flight Experiments

The pilot completed two flights in the X-15 with the single-error-needle display system. Both were high altitude flights similar to that depicted in figure 1. A time history of a few parameters telemetered to a ground station during these flights is presented in figures 9(a) and 9(b).

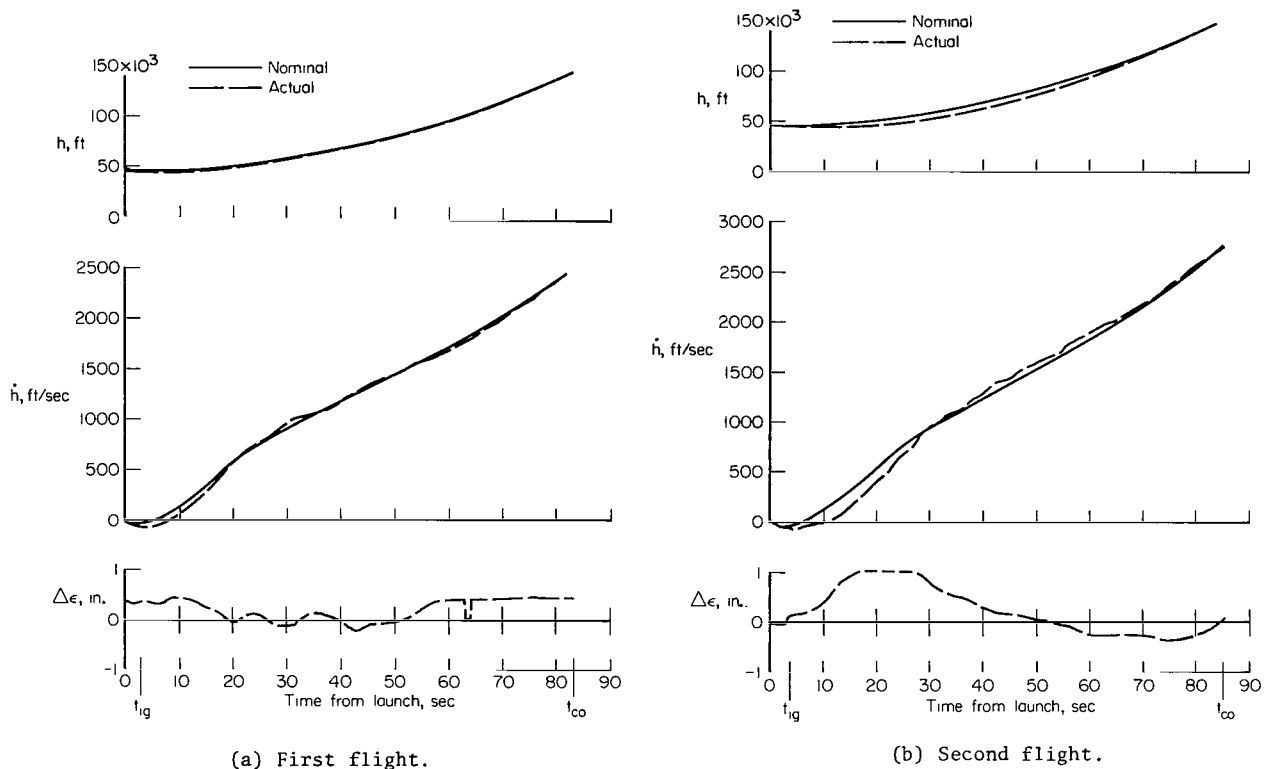


Figure 9.- Time histories of flight experiments with single-error-needle guidance system.

During the first flight (fig. 9(a)) the pilot flew the vehicle so that its trajectory remained very close to the nominal trajectory throughout the boost phase. The excursions about the null of the error signal, $\Delta\epsilon$ were about ± 0.2 inch, which is slightly larger than the excursions during the simulated flights (see fig. 8(a)).

At about 63 seconds into this flight, the pilot observed an anomalous behavior of the error display. The needle changed from about 0.2 inch positive to a null position for about one second and then returned to 0.2 inch positive. At that point, the pilot abandoned the error guidance system and reverted to the primary guidance (θ profile). Despite the external disturbances of a real flight environment and the anomalous transient behavior of the error signal, the actual trajectory matched closely the reference trajectory throughout the boost flight.

The pilot of the second flight was low in his altitude rate during the initial pull-up maneuver. The error needle went to its positive limit until about 25 seconds into the boost phase. When the error needle commenced showing a decrease in error, the pilot did not respond as rapidly as the pilot of the first flight. It appears that the pilot of the second flight responded to the error signals in such a manner as to approach the nominal trajectory asymptotically.

Comparison of System Performance

The guidance display systems were compared on the basis of the ability of the pilot to achieve acceptable thrust cut-off conditions. The required accuracy at thrust termination for a typical launch vehicle is approximately $\pm 0.1^\circ$ in flight-path angle and ± 3000 ft (1000 m) in altitude with respect to the nominal trajectory values of these parameters. At orbit velocity an accuracy of $\pm 0.1^\circ$ in flight-path angle is equivalent to an accuracy of approximately ± 45 ft/sec in altitude rate. The trajectory accuracy requirements on altitude and altitude rate at thrust termination for the X-15 are approximately the same, ± 3000 ft and ± 45 ft/sec, respectively.

The altitude and altitude-rate errors at thrust termination for the simulation tests and the two flight experiments are presented in figure 10.

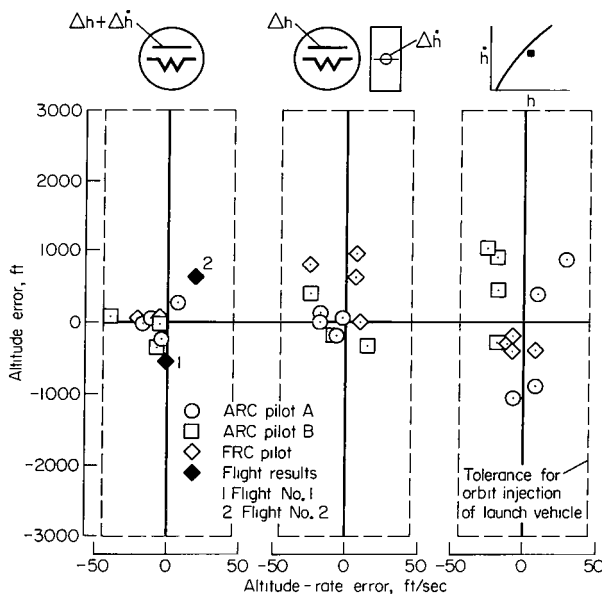


Figure 10.- Guidance errors at thrust termination.

The dashed lines in this figure represent the accuracy requirements of a large launch vehicle at thrust termination. The results indicate that with either of the three guidance systems, the pilot was able to guide the vehicle so that the cut-off conditions were within the prescribed accuracy requirements. Generally the pilot was able to match the reference altitude better with the single-error-needle system than with the other two systems. (The data in fig. 10 indicate a maximum altitude error of about 400 ft for the single-error-needle system.) With the other two systems, the altitude error increased by a small amount. The probable reason for this result is as follows. The flight-path angle at a given velocity at thrust termination determines the flight range of the X-15. The pilot must maneuver the X-15 so that it has the correct flight-path angle to reach the desired landing site. If he is presented the climb-rate error and altitude error on separate indicators, he will accept a small error in altitude in order to achieve a more accurate climb rate at thrust termination.

The thrust termination conditions of the two flight experiments are presented in figure 10 and are compared with the simulator results. Although both flights resulted in slightly larger errors in altitude than the simulated flights, the altitude-rate error was approximately the same as with the simulation data. On the basis of these limited results, there appears to be no adverse effect of real flight environment on the ability to guide with this guidance scheme.

CONCLUDING REMARKS

With either of the three guidance display systems investigated (single-error needle, dual-error needle, and x-y display), the pilot was able to guide during simulated flights to an accuracy in altitude and altitude rate within the accuracy required for large launch vehicles.

Although the limited flight data (two flights) indicated a slightly greater altitude error at thrust termination than the results of the simulation data, the errors were still within the prescribed limits of altitude and altitude rate.

Ames Research Center
National Aeronautics and Space Administration
Moffett Field, Calif., 94035, Sept. 8, 1969

APPENDIX

ANALYSIS OF CLOSED-LOOP GUIDANCE

A review of the time history of the single-error-needle system indicated a very lightly damped oscillation of the error signal, $\Delta\epsilon$, with a period of about 12 to 20 seconds and a simple analysis was made to determine its cause. For the calculations, the pilot was assumed to be a simple gain and pure time delay. The delay time was approximated by a simple first-order Padé approximation,

$$Ke^{-Ts} = -K \frac{s - (2/T)}{s + (2/T)}$$

where K is the gain of the pilot in the loop.

The value of T , time delay, was assumed to be about 0.5. This is somewhat higher than the value from single-axis, single-loop data of reference 6; however, other investigations (e.g., refs. 9 and 10) indicate that a value above 0.5 is not unreasonable when the pilot is involved in a complete task of monitoring a panel and controlling about three axes under real flight environment.

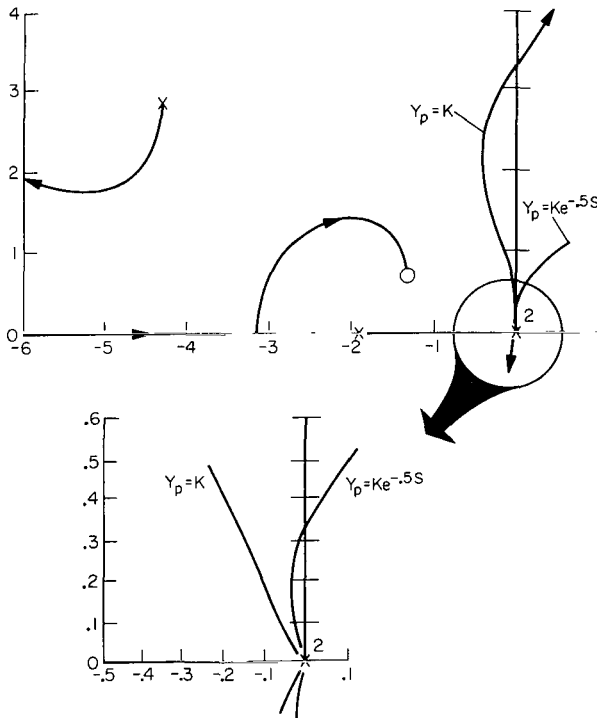


Figure 11.- Root locus plot of guidance loop with two transfer functions for human pilot.

The root locus plots presented in figure 11 are the results of the analysis of the single-error-needle system. The particular flight conditions chosen from this analysis were $h = 85,000$ ft and $M = 3.0$, corresponding to the characteristics shown in figure 2. The low frequency poles and zeros which do not affect the manual control system analysis have been omitted from the plot.

The significant point that may be interpreted from this plot is that with the time delay which may be considered reasonable (0.5) for a real flight environment, the pilot must operate at a low gain in the guidance loop. With this time delay, if the pilot operates near his maximum gain for a stable system (approximately where the root locus crosses the jw axis) the natural frequency of the error signal would be about 0.33 rad/sec which would result in a very lightly damped oscillation

with a period of about 18 seconds. This corresponds to the frequencies noted for the oscillating error signal in the simulator tests and the first flight experiments. Generally the oscillation periods ranged from 12 to 20 seconds throughout the tests with the single-error-needle system.

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